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LOW PMD OPTICAL FIBER LINK, AND METHOD OF MAKING THE SAME

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DESCRIPTION

9 The present invention generally relates to the field of optical fibers and to manufacturing methods thereof. More particularly, the invention concerns an optical fiber link featuring a low Polarization Mode Dispersion (shortly, PMD), and a method of realizing it.

99 Optical signals transmitted through single-mode optical fibers comprise two orthogonal polarization modes (typically denoted Transverse Electric, or TE, and Transverse Magnetic, or TM). In case the fiber has a perfectly cylindrical core of uniform diameter, the two modes TE and TM propagate at a common velocity. However, in real optical fibers the 99 cylindrical symmetry of the core may be disrupted due to shape defects or non-uniform stresses. As a result, a phase difference can accumulate between the two modes as they propagate, and the fiber is said to exhibit "birefringence". In particular, the birefringence introduced by shape and 99 stress asymmetry is known as "intrinsic linear birefringence".

The structural and geometrical irregularities of the optical fiber that give rise to birefringence typically originate from the fiber preform itself, and are modified 99 during the process of drawing the fiber. This process is usually carried out by means of an apparatus known as a "drawing tower", starting from a glass preform. In practice, after the preform has been placed in vertical position and heated to a temperature above the softening point within a 99 suitable furnace, the molten material is drawn downwards at a controlled velocity in such a way as to produce a threadlike element that forms the optical fiber itself. In this process, asymmetrical stresses are typically applied to

the fiber.

In a birefringent fiber, the two components TE and TM of the fundamental optical mode, initially in phase with each other, return to be in phase again only after a certain propagation length, commonly known as the "beat length" (L_B). In other words, the beat length is the period of repetition of a certain state of polarization (on the assumption that the fiber maintains a constant birefringence over this length). A further characteristic parameter of a birefringent fiber is the "correlation length" (L_F), which is defined as the distance over which the autocorrelation function of the birefringence is $1/e$ times its maximum value.

In the so-called "polarization-preserving" optical fibers, asymmetry is deliberately introduced into the fiber to generate birefringence. However, in ordinary (i.e., non-polarization-preserving) fibers, birefringence is detrimental to the fiber performance.

In fact, when pulsed signals are transmitted into an optical fiber, birefringence is a cause of pulse spreading, since the two polarization components, TE and TM, travel at different group velocities (i.e. become dispersed). This phenomenon, known as Polarization Mode Dispersion (PMD), has been widely studied in recent years because of its importance in periodically amplified light guide systems.

Typically, the phenomenon of PMD leads to a limitation of the width of the signal transmission band and, consequently, a degradation of the performance of the optical fibers along which the aforesaid signals are transmitted. This phenomenon is therefore undesirable in systems of signal transmission along optical fibers, especially in those operating over long distances, in which it is necessary to minimize any form of attenuation or

dispersion of the signals to guarantee high performances in transmission and reception.

U.K. patent application GB-A-2101762 considers the effects on PMD of post-draw fiber twisting and observes that, although such twisting reduces the PMD resulting from intrinsic linear birefringence, it introduces torsional stresses that generate a substantial circular birefringence due to the photo-elastic effect. Twisting a drawn fiber thus reduces the bandwidth limitation due to one effect, whilst replacing it with another. The same patent application thus proposes to spin the preform during drawing, so that twisting can be effected whilst keeping the fiber material substantially unstressed. Spinning is performed at a relatively high rate, so that its spatial repetition frequency, or spin pitch, is small compared to the beat length due to intrinsic birefringence; as a result, an optical fiber can be produced wherein the contribution of birefringence due to form and stress asymmetries is greatly reduced. Such a fiber is termed "spun" fiber, to distinguish it from a (post-drawn) twisted fiber. Conveniently, the preform is spun at a substantially constant rate, but it could even reverse in direction, oscillating from a right-handed to a left-handed twist.

In the present description, the same distinction as above will be made between "spin" and "twist". More precisely, the terms "spin" and "twist" are herein used to identify two different types of torsion of the fiber: "spin" identifies a torsion that is frozen-in during drawing, being applied to a viscous portion of the fiber and kept as a structural modification of the fiber while cooling; differently, "twist" identifies an elastic torsion of the fiber, which is present when a torque is applied to a portion of fiber whose ends are constrained against

rotation. In other words, although both spin and twist alter the fiber in shape, so that parts previously in the same straight line are located in a spiral curve, a twisted fiber will rotate back to its original shape when its ends are released from the rotation constraint, while a spun fiber will keep this alteration as an intrinsic and permanent deformation. Due to spinning, the fiber undergoes a rotation of its polarization axes. As a result, when optical pulses are transmitted into the optical fiber, they propagate alternately on the slow and fast birefringence axes, thus compensating the relative delay and reducing the pulse spreading. This is equivalent to having a local effective refractive index for the optical pulses equal to the mean refractive index on the two axes, the average being taken over the pulse length along the fiber.

Theoretical studies have shown that the dominant process for the reduction of PMD in a spun fiber is the averaging of the local fiber anisotropy by the rapid procession of the axes of asymmetry along the fiber.

The United States patent US 4,504,300, relating to a technique for making an optical fiber having chiralic structure, addresses drawbacks related to preform rotation and proposes a new spinning technique, consisting in rotating the fiber instead of the preform. In particular, a device is disclosed comprising means disposed just below the preform for twisting the fiber during fiber drawing. The twisting means comprise a rotating hoop supporting three pulleys. The twisted fiber is coated by coating means, followed by cooling by fast-cooling means that facilitate freezing-in of the twist.

The United States patent US 5,418,881 proposes to arrange the device adapted to apply the torque to the fiber downstream of the coating station, so as to avoid damaging

the fiber surface. In particular, the torque is applied by alternately canting in clockwise and counterclockwise direction a fiber guiding roll having a rotation axis which extends perpendicularly to the drawing axis of the fiber. In 7 this way, in at least a portion of the fiber the spin impressed to the fiber is alternately clockwise and counterclockwise. The same patent states that applying a clockwise and a counterclockwise torque to the fiber substantially prevents introduction of an elastic twist to the fiber.

99 The United States patent application N. US2001/0020374 proposes a new device that overcomes some drawbacks of the canting-roll technique and allows both unidirectional and alternate spinning, but also states that alternate spinning is to be considered as preferable since it prevents the 99 presence of residual torsions (i.e., of a residual twist) on the fibers wound onto the collecting spool, thus making easier both the unwinding and wiring operations of the same.

In the United States patent US 5,943,466, it is proposed to spin the fiber during drawing in accordance with 99 spin functions which are not substantially constant (in the sense that they change substantially as a function of distance along the length of a fiber or as a function of time), not substantially sinusoidal, and have sufficient variability (e.g. sufficient harmonic content) to provide a 99 substantial reduction in PMD for a plurality of beat lengths.

The Applicant has found some other drawbacks of the alternate spinning technique, not previously highlighted. Alternate spinning may for example cause a relatively low 99 mechanical efficiency of the spinning device, due to the continuous accelerations and decelerations. Moreover, with respect to a unidirectional spin, an alternate spin requires a relatively high peak profile amplitude to compensate those

positions of the profile where the rotation slows down to change direction and, therefore, to guarantee a sufficient average spin rate. Besides all this, the sites where the spin rate is zero are detrimental for the PMD, because there
9 is an increase of the effective birefringence seen by the pulse, and so a higher contribution for PMD.

The paper by A. Galtarossa *et al.*, "PMD statistical properties of constantly-spun fibers", ECOC-IOOC 2003 Proceedings, Vol. 4, Th. 1.7.4, and the paper by A.
99 Galtarossa *et al.* "Polarization mode dispersion properties of constantly spun randomly birefringent fibers", Optics Letters, vol 28 No.18, September 2003, pp. 1639-1641 report the PMD induced delay (*i.e.* the mode delay - in ps - induced by PMD or, equivalently, the mean fiber Differential Group
99 Delay, or "DGD") of unidirectionally-spun fibers. It can be shown that, while in an unspun fiber or an alternately spun fiber the PMD induced delay increases proportionally to the square root of the fiber length, in a unidirectionally-spun fiber the PMD induced delay has a higher increase rate, and
99 only asymptotically increases proportionally to the square root of length. In particular, the PMD induced delay in a unidirectionally-spun fiber asymptotically increases at the same rate as the PMD induced delay of an unspun fiber having the same beat length L_B and the same correlation length L_F .
99 Advantageously, a PMD coefficient, hereinafter indicated with PMD_c , defined as the mean fiber DGD divided by the square root of length, is introduced. For unspun or alternately spun fibers, this parameter is independent from the fiber length.

99 In greater detail, reference is made to **Figure 1**, wherein a theoretical diagram of the average of the squared DGD $\langle \Delta\tau^2 \rangle$ (in ordinate, unit ps^2) as a function of the propagation distance (in abscissa, unit km) is shown for an

unspun fiber (curve (a)) with a typical (constant) PMD_c (e.g., $0.1 \text{ ps/km}^{1/2}$), an alternately spun fiber (curve (b)) with a typical (constant) PMD_c (e.g., $0.04 \text{ ps/km}^{1/2}$) and a unidirectionally spun fiber (curve (c)) with the same beat length L_B and the same correlation length L_F as the unspun fiber. From the diagram, it can be appreciated that the slope of curve (c) (i.e. the increase rate of $\langle \Delta\tau^2 \rangle$) is not constant, but increases with the propagation distance up to a constant value corresponding to the slope of curve (a).

The length over which the slope changes can be denoted as a transient length. Since the PMD_c is proportional to the square root of $\langle \Delta\tau^2 \rangle$ divided by the square root of the fiber length, it is expected that such a coefficient increases with the propagation distance (i.e. with the fiber length), differently from the PMD_c of unspun and alternately spun fibers, which is constant. In particular, for the unidirectionally spun fiber, the increase of the PMD_c will be more rapid in the initial transient, before the increase rate of the PMD_c becomes similar to that of the unspun fiber; after the transitory, the PMD_c increases very slowly reaching asymptotically the PMD_c of the unspun fiber. As already predicted in the article by Galtarossa et al., "Optimized Spinning Design for Low PMD Fibers: An Analytical Approach" Journal of Lightwave technology vol. 19 no.10 Oct. 2001 pp. 1502-1512, the initial PMD_c increase is the one predicted in the deterministic regime.

In the above-cited articles by Galtarossa, it is also described that the magnitude of the spin period changes the length of the above-mentioned transient regime, and that a transient characteristic length L_T can be defined for unidirectionally spun fibers (curve (c) in **Figure 1**):

$$L_T = L_F \left(1 + \frac{4L_B^2}{P^2} \right)$$

where p is the spinning period, L_F the correlation length and L_B the beat length. The transient characteristic length L_T is equal to the intercept of the linear asymptotic behavior of curve (c) with the abscissa axis. The
9 propagation distance (or length of fiber span) required to approach the regime PMD behavior of the unspun fiber is estimated to be of some transient characteristic lengths.

Assuming that the parameters appearing in the above formula fall within the typical ranges: $L_F = 1 \div 20$ m, $L_B = 5$
99 $\div 15$ m, and $p = 0.1 \div 1$ m, the transient characteristic length L_T may vary between 0.1 and 1,800 km, covering four orders of magnitude. If the transient characteristic length L_T is much greater than the link length, the PMD_c increase remains moderate. On the contrary, when the transient
99 characteristic length L_T is comparable to or smaller than the link length, the PMD_c increase over the link becomes significant and can be detrimental to signal transmission.

Thus, unidirectionally spun fibers with short transient characteristic lengths suffer from a growth of the PMD_c with
99 the fiber length, which cancel the advantage of using a spun fiber.

In view of the state of the art outlined in the foregoing, it appears that an optimum solution to the problem of PMD in fibers does not exist: unspun fibers have
99 in fact a PMD which, for several applications, is too high; on the other hand, alternately spun fibers exhibit the series of problems previously mentioned. From the above theoretical considerations it also comes out that unidirectionally spun fiber may be preferable with respect
99 to unspun fibers only for relatively short fiber lengths, because they experience a growth of their PMD_c as the length increases, which becomes asymptotically equal to the one of unspun fibers.

Thus, it has been an object of the present invention to devise a solution to these problems.

9 In particular, it has been an object of the present invention to provide an optical fiber link, and a method of realizing it, featuring a significant limitation of the PMD_c increase with fiber length.

99 With these objects in mind, the Applicant has found that the increase in the PMD_c exhibited by unidirectionally spun fibers can be completely eliminated or substantially reduced if an optical fiber link is made of unidirectionally spun fiber spans, of appropriate lengths, with opposite helicity, spliced one to the other to form the optical fiber. With "helicity", it is here intended the fiber spin direction, which can be either right-handed or left-handed 99 (i.e. clockwise or counter clockwise).

Therefore, an optical fiber link according to the present invention includes at least a first and a second optical fiber spans unidirectionally-spun in opposite directions and joined to each other. Preferably, the optical 99 fiber link comprises a first type of fibers unidirectionally-spun in a first direction, and a second type of fibers unidirectionally-spun in the opposite direction, the fibers of the first type being alternated to the fibers of the second type, i.e. fiber spans of opposite 99 helicity are alternated to each other.

According to an aspect of the present invention, an optical fiber link is provided for, as set forth in appended independent optical fiber link claim 1.

99 In brief, the optical fiber link comprises a plurality of optical fiber spans, joined one to the other, said plurality of optical fiber spans including at least one first unidirectionally-spun optical fiber span and at least one second unidirectionally-spun optical fiber span having

mutually opposite spinning directions.

For the purposes of the present invention, the terms "spin", "spinning" and "spun" all relate to a torsion that is frozen-in during drawing, being applied to a viscous
9 portion of the fiber and kept as a structural modification of the fiber while cooling. In other words, a spun fiber will keep this alteration as an intrinsic and permanent deformation.

Also, for the purposes of the present invention, with
99 "unidirectional spin" it is intended a spin that occurs on a same direction apart from possible local inversions, for example due to fiber slippage in the spinning device or in the traction device.

Preferably, the unidirectional spin here considered is
99 constant, but it may also derive from the superposition of a constant spin function and a variable spin function, the variable spin function having preferably a small amplitude and a long period.

Preferably, the first unidirectionally-spun optical
99 fiber span and the second unidirectionally-spun optical fiber span are joined to each other.

In a preferred embodiment of the present invention, the plurality of optical fiber spans includes a plurality of first optical fiber spans, and a plurality of second optical
99 fiber spans, the first optical fiber spans and the second optical fiber spans being spans of unidirectionally spun optical fibers having mutually opposite spinning directions. The first optical fiber spans and the second optical fiber spans are alternated to each other in the optical fiber
99 link.

In an embodiment of the present invention, the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span have substantially

a same length.

In particular, the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span may have substantially a same spin rate.

9 Preferably, the number of first optical fiber spans and second optical fiber spans is odd.

According to another aspect of the present invention, an optical cable line as set forth in appended claim 7 is provided.

99 Summarizing, the optical cable line includes a plurality of optical cable trunks joined to each other. Said plurality of optical cable trunks comprises at least a first optical cable trunk and a second optical cable trunk, the first optical cable trunk including a first optical fiber span unidirectionally-spun in a first direction, and the 99 second optical cable trunk including a second optical fiber span unidirectionally-spun in a second direction opposite to the first direction, the first and the second optical fiber spans being optically linked to each other.

99 In particular, the first and the second optical fiber spans are joined to each other.

In an embodiment of the present invention, the first and the second optical fiber spans have substantially a same length.

99 In particular, the first and the second optical fiber spans may have substantially a same spin rate.

According to an embodiment of the present invention, the plurality of optical cable trunks include a plurality of first optical fiber spans, and a plurality of second optical 99 fiber spans joined to each other to form an optical fiber link, the first optical fiber spans and the second optical fiber spans being unidirectionally-spun optical fibers having mutually opposite spin directions, and the first

optical fiber spans and the second optical fiber spans being alternated to each other in the optical fiber link.

9 In particular, in an embodiment of the present invention at least one optical cable trunk of said plurality of optical cable trunks has an optical core including a plurality of unidirectionally-spun optical fiber spans having a same spin direction.

99 In another embodiment of the invention, at least one optical cable trunk of said plurality of optical cable trunks has an optical core including at least two unidirectionally-spun optical fiber spans having opposite spin directions.

Preferably, the total number of optical cable trunks is odd.

99 According to still another aspect of the present invention, a method of realizing an optical fiber link as set forth in appended independent method claim 15 is provided.

The method comprises:

99 providing at least a first span of optical fiber, unidirectionally-spun in a first direction;

providing at least a second span of optical fiber, unidirectionally-spun in a second direction opposite to the first direction; and

99 joining the first span and the second span together at a respective end thereof.

According to a further aspect of the present invention, a method of producing an optical cable as set forth in appended claim 16 is provided.

99 The method comprises providing a plurality of optical fibers to a cable manufacturing line, wherein said plurality of optical fibers comprises at least a first optical fiber being unidirectionally-spun in a first direction, and at

least a second optical fiber being unidirectionally-spun in a second direction opposite to the first direction.

According to a still further aspect of the present invention, a method of realizing an optical cable line as
9 set forth in appended claim 17 is provided.

The method comprises forming a plurality of optical cable trunks, each one including at least one optical fiber span, and joining the optical cable trunks one to another.

The step of forming a plurality of optical cable trunks
99 comprises forming at least one first trunk including a first optical fiber span unidirectionally-spun in a first direction, and forming at least one second trunk including a second optical fiber span unidirectionally-spun in a second direction opposite to the first direction; said joining the
99 optical cable trunks one to another includes optically linking the first optical fiber span to said second optical fiber span.

These and other features and advantages of the present invention will be made apparent by the following detailed
99 description of an embodiment thereof, provided merely by way of non-limitative example, description that will be conducted making reference to the attached drawings, wherein:

Figure 1 is a diagram showing the predicted variation
99 of the average of the squared Differential Group Delay (DGD) (in ordinate) with the propagation distance (in abscissa) for: an unspun fiber (curve (a)), an alternately spun fiber (curve (b)) and a unidirectionally spun fiber (curve (c)) with the same beat length L_B and the same correlation length
99 L_F as the unspun fiber;

Figure 2 schematically shows a portion of an optical fiber link according to an embodiment of the present invention, comprising alternated, unidirectionally spun

fiber spans having mutually opposite helicity;

Figures 3A and 3B show diagrams of the predicted variation of the PMD_c (in ordinate, unit ps/km^{1/2}) with the propagation distance (in abscissa, unit km) for the fiber of Figure 2 for various lengths of the alternated fiber spans, and for two different values of the fiber transition characteristic length;

Figure 4A shows in transverse section an optical cable containing optical fibers in accordance to an embodiment of the present invention;

Figure 4B schematically shows in lateral view a portion of an optical cable line in accordance with the present invention;

Figure 5 is a diagram showing the predicted variation with the propagation length (in abscissa, unit km) of the ratio between the average of the squared DGD values to the square of the averaged DGD values (in ordinate) for a fiber with the same parameters of Figure 3A, with alternated spans length of 5 km;

Figures 6A to 6F are diagrams showing the statistical distribution of the DGD values for the same fiber of Figure 5 at propagation distances indicated in Figure 5 with the letters a) to f) respectively;

Figure 7 shows a drawing tower adapted to drawing unidirectionally spun fibers;

Figure 8 illustrates a spinning device suitable to be used in the drawing tower of Figure 7;

Figure 9 shows a twist apparatus suitable to be used in the drawing tower of Figure 7;

Figure 10 illustrates a re-spooling apparatus; and

Figure 11 shows a twist apparatus to be used in the drawing tower of Figure 7, in alternative to the apparatus of Figure 9.

With reference to the drawings, in **Figure 2** a portion of an optical fiber link according to an embodiment of the present invention is shown very schematically.

By optical fiber link there is intended an optical
9 fiber made up of two or more optical fiber spans, joined to each other.

The optical fiber link, indicated globally as **300**, is for example of the type used in optical fiber cables for optical communication systems.

99 The optical fiber link **300** (the portion of which shown in **Figure 2** being for example an intermediate portion along the overall length of the optical fiber link) comprises a plurality of optical fiber segments or spans ..., **305**_(k-1), **305**_k, **305**_(k+1), **305**_(k+2), **305**_(k+3), **305**_(k+4), **305**_(k+5), **305**_(k+6), ...,
99 of shorter length, joined one to another at respective free ends to form the optical fiber link **300**; in jargon, the operation of joining of two optical fiber segments together is referred to as "splicing"; in the drawing, the points where two generic optical fiber spans ..., **305**_(k-1), **305**_k,
99 **305**_(k+1), **305**_(k+2), **305**_(k+3), **305**_(k+4), **305**_(k+5), **305**_(k+6), ..., are spliced together are schematically indicated by **310**.

According to an embodiment of the present invention, the optical fiber spans ..., **305**_(k-1), **305**_k, **305**_(k+1), **305**_(k+2), **305**_(k+3), **305**_(k+4), **305**_(k+5), **305**_(k+6), ..., are segments or spans
99 of unidirectionally spun optical fibers. In particular, spans of unidirectionally spun optical fibers with mutually opposite spinning helicity (right-hand, or σ_+ , helicity and left-hand, or σ_- , helicity) are exploited to form the optical fiber link **300**, and the unidirectionally spun fibers
99 spans with right-hand, or σ_+ , spinning helicity are alternated to the unidirectionally spun fibers spans with left-hand, or σ_- , spinning helicity, as schematically depicted in the drawing. Preferably, the unidirectional spin

of the different fiber spans is constant in module.

Due to the fact that splicing together fibers with opposite helicity interrupts the transients of the PMD_c of a unidirectionally-spun fiber towards the unspun fiber value, the growth of the PMD_c of the optical fiber link 300 with the fiber link length, discussed in the introductory part of the present description, may be substantially reduced by the above-described provision in the fiber link 300 of both type of fiber spans.

In principle, the lengths of the individual fiber spans ..., $305_{(k-1)}$, 305_k , $305_{(k+1)}$, $305_{(k+2)}$, $305_{(k+3)}$, $305_{(k+4)}$, $305_{(k+5)}$, $305_{(k+6)}$, ..., might be whatsoever, but, as will be shown in the following, a careful choice of such lengths allows substantially reducing, or even eliminating, the effect of growth of the PMD_c with the fiber length (thereby, after a certain length, a practically constant PMD_c is achieved, lower than the one of the single-helicity, unidirectionally-spun fiber).

In particular, if the spin rates of the unidirectionally spun optical fibers with σ_+ helicity have substantially the same magnitude (modulus) as the spin rates of the unidirectionally spun optical fibers with σ_- helicity, the best results in terms of suppression of the PMD_c growth with the fiber link length are achieved by alternating, along the fiber link 300, σ_+ and σ_- optical fiber spans of substantially same lengths. However, if the spin rates of the unidirectionally spun optical fibers with σ_+ helicity have a different magnitude (modulus) from the spin rates of the unidirectionally spun optical fibers with σ_- helicity, the lengths of the different σ_+ and σ_- optical fiber spans should depend on the respective spin rate absolute values.

Reference is now made to **Figures 3A** and **3B**, which are

diagrams of the predicted variation of the PMD_c (in ordinate, unit $\text{ps}/\text{km}^{1/2}$) with the propagation distance (in abscissa, unit km) for the fiber link 300 for various lengths of the alternated fiber spans ..., $305_{(k-1)}$, 305_k ,
9 $305_{(k+1)}$, $305_{(k+2)}$, $305_{(k+3)}$, $305_{(k+4)}$, $305_{(k+5)}$, $305_{(k+6)}$, ..., that make up the fiber link 300, and for two different values of the fiber transient characteristic length L_T . The curves have been derived in accordance with the teaching of Galtarossa et al., "Polarization mode dispersion properties of constantly spun randomly birefringent fibers", Optics Letters, vol 28 No.18, September 2003, pp. 1639-1641, relative to fibers with a single spin direction.

In particular, the diagram of **Figure 3A** relates to an optical fiber link 300 made up of alternated
99 unidirectionally spun fiber spans of opposite helicity having a spinning period $p = 0.25$ m, a beat length $L_B = 7$ m, a correlation length $L_F = 10$ m, and consequently a transient characteristic length $L_T = 32$ km. The diagram of **Figure 3B** relates instead to a similar optical fiber link 300, but
99 having a spinning period $p = 0.5$ m, and thus featuring a transient characteristic length $L_T = 8$ km. In both cases, the evolution of the PMD_c with the propagation distance for alternated fiber spans ..., $305_{(k-1)}$, 305_k , $305_{(k+1)}$, $305_{(k+2)}$,
 $305_{(k+3)}$, $305_{(k+4)}$, $305_{(k+5)}$, $305_{(k+6)}$, ..., of length L_c equal to 5
99 km, 10 km, 20 km, 40 km and for an infinite span length (i.e. for a single helicity fiber) is shown.

It can be appreciated that, in both cases, when alternating optical fiber spans unidirectionally-spun with opposite helicity, the PMD_c after a transient attains a
99 substantially constant value which is lower than that of the single-helicity unidirectionally spun fiber, and hence of the unspun fiber with the same beat length L_B and correlation length L_F . So, the typical behavior of the

single-helicity, unidirectionally-spun fiber is substantially transformed in a behavior similar to that of an alternately spun fiber.

Comparing the two diagrams, it can also be appreciated
9 that the smaller the value of the transient characteristic length L_T , the smaller the span length L_c necessary to achieve a same value of the PMD_c . It can be appreciated by those skilled in the art that an optimum L_c value can always be evaluated from the link length, the maximum allowed
99 number of spans, and the transient characteristic length.

From the two diagrams of **Figures 3A** and **3B** it can also be noted that, for a value of the beat length $L_B = 7$ m and a value of the fiber correlation length $L_F = 10$ m, a span length L_c substantially equal to the transient
99 characteristic length L_T gives a PMD_c of about $0.04 \text{ ps/km}^{1/2}$, that is a value comparable to the one of the commercially available, alternately spun optical fibers.

The optical fiber spans ..., $305_{(k-1)}$, 305_k , $305_{(k+1)}$, $305_{(k+2)}$, $305_{(k+3)}$, $305_{(k+4)}$, $305_{(k+5)}$, $305_{(k+6)}$, ..., are typically
99 cabled and the optical fiber link 300 previously described is therefore typically part of an optical cable line. As schematically shown in **Figure 4B** (the drawing is not in scale), an optical cable line 80 typically comprises a plurality of trunks of optical cable ..., $805_{(k-1)}$, 805_k ,
99 $805_{(k+1)}$, $805_{(k+2)}$, $805_{(k+3)}$, $805_{(k+4)}$, ..., joined in series (*i.e.* concatenated) one to the other. Each cable trunk ..., $805_{(k-1)}$, 805_k , $805_{(k+1)}$, $805_{(k+2)}$, $805_{(k+3)}$, $805_{(k+4)}$, ..., includes a respective optical fiber span ..., $305_{(k-1)}$, 305_k , $305_{(k+1)}$, $305_{(k+2)}$, $305_{(k+3)}$, $305_{(k+4)}$, $305_{(k+5)}$, $305_{(k+6)}$, ...

Each optical cable trunk ..., $805_{(k-1)}$, 805_k , $805_{(k+1)}$, $805_{(k+2)}$, $805_{(k+3)}$, $805_{(k+4)}$, ..., has a typical length in the
99 range from approximately 2 km to approximately 10 km.

With reference to **Figure 4A**, a cross-sectional view of

an optical cable along the optical cable line 80 is shown; the optical cable typically comprises an optical core 81 containing a plurality of optical fibers 800.

The optical core 81 may be of the "tight" type (as the
9 one illustrated in the drawing), wherein the optical fibers 800 are embedded into a polymeric matrix disposed around a strength member 83, or of the "loose" type, wherein the fibers 800 are loosely housed within a single buffer tube centrally disposed within said cable, or within a plurality
99 of buffer tubes stranded around a central strength member. Around the optical core 81, the optical cable 80 is provided with reinforcing elements 84 and protective sheaths 85, 86.

In "tight" type cabling, the contact between the fiber and the polymeric matrix prevents the twist imparted to the
99 fibers to be released. In "loose" type cabling, the twist imparted on the fiber is not released, for typical cable lengths, due to friction between the fiber and the buffer tube, possibly enhanced by the presence of a jelly filler.

From a manufacturing viewpoint, the optical fiber link
99 300 can be obtained starting by producing two sets of unidirectionally spun optical fibers having opposite spinning helicity. The two sets of fibers are properly labeled, for example σ_+ and σ_- , so as to be able to distinguish fibers of one set from those of the other.
99 Accordingly, the first set will be said to have a σ_+ helicity and the second set a σ_- helicity.

Preferably, in order to ease the task of alternating fiber spans with mutually opposite spinning helicity, the unidirectionally spun optical fiber with σ_+ helicity has
99 substantially the same spin rate as the unidirectionally spun optical fiber with σ_- helicity.

Later on in the present description, an apparatus suitable to produce unidirectionally spun optical fibers

will be described in detail, being intended that the way, and the apparatuses, by means of which the unidirectionally spun optical fibers are obtained are not limitative to the present invention.

9 Once two sets of fibers (σ_+ and σ_-) with opposite helicity have been produced, spans of predetermined length of these fibers are used in a cabling process of a known type to produce an optical cable such as the one illustrated in **Figure 4A**.

99 A plurality of optical cable trunks is thus formed. These optical cable trunks are then connected one to another by known techniques, to form an optical cable transmission line such as the one illustrated in **Figure 4B**.

99 According to a first embodiment, each optical cable trunk may include, in its optical core, a certain number (for example, half of the total number) of fibers with a clockwise helicity and a certain number (for example, of half the total number) of fibers with a counter clockwise helicity. In this case, the optical cable trunks may be
99 identical to each other.

99 According to a second embodiment, each optical cable trunks may include fibers of a single type, i.e. either of clockwise helicity or of counter-clockwise helicity. In this case, cable trunks including only σ_+ fibers and cable trunks
99 including only σ_- fibers are produced.

99 Then the optical cable trunks are concatenated to each other to form the optical cable line 80. To join together two optical cable trunks, a connecting device of a known type can be used, such as the optical fiber connecting assembly described in the United States patent US 5,778,131 or the compact joint Oasys^(R) realized by Pirelli. In practice, the fibers exiting the ends of the two cable trunks are housed and routed in the connecting device, and

then they may be spliced end-to-end by a fusion splicer of a known type, such as model FSM-40S/40S-B by Fujikura.

The optical fiber spans ..., 305_(k-1), 305_(k+1), 305_(k+3), 305_(k+5), ..., are so spliced to form the optical fiber link 300. In particular, the optical fiber link 300 is formed by splicing alternately a fiber span ..., 305_(k-1), 305_(k+1), 305_(k+3), 305_(k+5), ..., from the right-handed (left-handed) spun fiber set σ_+ (σ_-), with a fiber span ..., 305_k, 305_(k+2), 305_(k+4), 305_(k+6), ..., from the left-handed (right-handed) spun fiber set σ_- (σ_+).

By properly choosing the spin rate of the σ_+ and σ_- optical fiber spans, in particular by making the transient characteristic length L_T suitably longer than the typical cable trunk length, the optical cable line obtained by joining optical cable trunks including optical fibers spans of opposite (σ_+ and σ_-) helicity has a low and substantially constant PMD_c.

If the optical cable trunks include optical fiber spans of a same helicity (either right-handed, i.e. σ_+ , or left-handed, i.e. σ_-), the optical cable 80 is preferably made by alternating cable trunks including σ_+ fiber spans with cable trunks including σ_- optical fiber spans.

Alternatively, if the optical cable trunks include both σ_+ and σ_- optical fiber spans, the optical cable is preferably made by joining the different cable trunks in such a way that σ_+ fibers spans are spliced with σ_- fiber spans.

The Applicant has investigated the PMD statistical properties of an optical fiber link such as the link 300.

It is known in the art that both unspun and alternately spun optical fibers present a Maxwellian statistical distribution of the DGD values. The Maxwellian distribution

is characterized by a ratio between the average of the squared DGD, $\langle \Delta\tau^2 \rangle$, and the square of the averaged DGD, $\langle \Delta\tau \rangle^2$, equal to:

$$r = \frac{\langle \Delta\tau^2 \rangle}{\langle \Delta\tau \rangle^2} = \frac{3\pi}{8} \approx 1.18$$

9 In **Figure 5** the numerically computed (predicted) ratio r is plotted as a function of the propagating length. The optical fiber link parameters are the same as for the fiber of the diagram of **Figure 3A**, with a span length $L_c = 5$ km. The ratio r exhibits strong oscillations superimposed to a
99 monotonous rise towards the asymptotic value, equal to 1.18. A value of r larger than 1.18 indicates a statistical dispersion of the DGD values distribution larger than that typical of the Maxwellian distribution. On the other side, a
99 value of r smaller than 1.18 indicates that the DGD values are less dispersed than in the Maxwell case.

Figures 6A to 6F are diagrams showing the statistical distribution of the DGD values at points (a) to (f) of **Figure 5**, respectively.

According to these results, an odd number of fiber
99 spans joined together guarantees a Gaussian-like DGD statistical distribution narrower than the Maxwellian one, as shown in **Figures 6A-6D**, and correspondently in the points marked (a)-(d) in **Figure 5**. Here and in the following
99 Figures, the dashed lines indicate the Maxwellian fit, and the solid lines the Gaussian fit. However, the narrowing of the distribution below the Maxwellian limit diminishes as the span number increases. On the other side, an even span number gives a DGD dispersion larger than, and asymptotically equal to, the Maxwellian distribution, as
99 shown in **Figures 6E and 6F**, and correspondently in the points marked as (e) and (f) in **Figure 5**.

In the following, an apparatus and a method to produce

unidirectionally spun optical fibers will be described in detail. It is understood that these apparatus and method are not limitative to the present invention, any other method, and apparatus, adapted to produce unidirectionally spun
9 fibers being suitable.

With reference to **Figure 7**, a drawing tower **1** comprises a plurality of devices that are substantially aligned along a vertical drawing axis **2** (whence the term "tower"). The choice of a vertical direction in order to perform the main
99 steps of the drawing process arises from the need to exploit the gravitational force so as to obtain, from a glass preform **3**, molten material from which an optical fiber **4** can be drawn.

In detail, the tower **1** comprises a furnace **6** for
99 performing a controlled melting of a lower portion of the preform **3** (also known as preform neckdown), a feeding device **7** for supporting the preform **3** and feeding it into the furnace **6** from the above, a traction device **8** (at a lower end of the tower) for pulling the fiber **4** from the preform
99 **3**, and a winding device **9** for storing the fiber **4** onto a reel **10**.

The furnace **6** may be of any type designed to produce a controlled melting of a preform. Examples of furnaces that can be used in the tower **1** are described in US 4,969,941 and
99 US 5,114,338.

Preferably, a cooling device **12**, for example of a type having a cooling cavity designed to be passed through by a flow of cooling gas, is situated underneath the furnace **6** for cooling the fiber **4** leaving it. The cooling device **12** is
99 arranged coaxially to the axis **2**, so that the fiber **4** leaving the furnace **6** can pass through it.

The tower **1** may also be provided with a tension-monitoring device **13** (for example of the type described in

the United States patent US 5,316,562), and a diameter sensor 14 of a known type, preferably positioned between the furnace 6 and the cooling device 12, for measuring the tension and the diameter of the fiber 4, respectively.

9 Preferably, the tower 1 further comprises a first and a second coating devices 15, 16 of a known type, positioned underneath the cooling device 12 in the vertical drawing direction and designed to deposit onto the fiber 4, as it passes through, a first protective coating and, 77 respectively, a second protective coating. Each coating device 15, 16 comprises, in particular, a respective application unit 15a, 16a which is designed to apply onto fiber 4 a predefined quantity of resin, and a respective curing unit 15b, 16b, for example a UV-lamp oven, for curing 77 the resin, thus providing a stable coating.

The traction device 8 may be of the single pulley or double pulley type. In the illustrated embodiment, the traction device 8 comprises a single motor-driven pulley (or "capstan") 18 that is designed to draw the fiber 4, already 77 coated, in the vertical drawing direction. The traction device 8 may be provided with an angular velocity sensor 19 that is designed to generate a signal indicating the angular velocity of the pulley 18 during its operation. The rotation speed of the pulley 18 and, therefore, the drawing speed of 77 the fiber 4, may be varied during the process, for example as a response to a diameter variation detected by detector 14.

The tower 1 further comprises a spinning device 20, positioned between the coating devices 15, 16 and the 77 traction device 8, for imparting a spin to the fiber 4 about its axis during drawing. For the purposes of the present description, the term "spin" denotes the ratio (disregarding a constant multiplication factor) between the angular

velocity of rotation dq/dt of the optical fiber (where q is the angle of rotation of the optical fiber measured with respect to a fixed reference point) and the velocity of drawing. The spin defined in this way is typically measured
9 in turns/m.

In one possible embodiment, illustrated in **Figure 8**, the spinning device **20** comprises a fixed support frame **21**, a DC motor **22** held by the frame **21** and a rotating member **23** held by the frame **21** and coupled to the motor **22** through a
99 belt transmission **24**. The belt transmission comprises a first driving pulley **24a** rigidly coupled to the motor **22**, a second driving pulley **24b** rigidly coupled to the rotating member **23** and a belt **24c** connecting the first driving pulley **24a** to the second driving pulley **24b**.

99 The rotating member **23** has a rotation axis corresponding to the axis **2**, i.e. to the axis of motion of the fiber **4** when entering and leaving the device **20**. The rotating member **23** comprises a first and a second sleeve-like end portion **23a**, **23b** (respectively upper and lower),
99 which are rotatably coupled to the support frame **21** by means of respective bearings **26** and which allows passage of the fiber there through. The second end portion **23b** is coupled with the second driving pulley **24b**.

99 The rotating member **23** comprises two arms **27a**, **27b**, extending from the first end portion **23a** to the second end portion **23b**. The arms **27a**, **27b** are substantially C-shaped, with a main straight central region parallel to the axis **2**, and are arranged symmetrically to each other with respect to the axis **2**. One of the two arms (the one indicated with **27b**
99 in the drawing) carries a first, a second, and a third idle-mounted rotating pulley **28a**, **28b**, **28c** (from up to down in the drawing), substantially aligned in a direction parallel to the axis **2**. The three pulleys **28a**, **28b**, **28c** have the

corresponding axes perpendicular to the axis 2 and are dimensioned so that the corresponding guiding grooves are substantially tangent to the axis 2.

Referring back to **Figure 7**, the tower 1 may also
9 comprise a tension-control device 30, commonly known as
"dancer", for adjusting the tension of the fiber 4
downstream the traction device 8. The tension-control device
30 is designed to counterbalance any variations in tension
of the fiber 4 between the pulley 18 and the winding device
99 9. The tension-control device 30 may comprise, for example,
a first and a second pulleys 30a, 30b that are mounted idle
and in a fixed position, and a third pulley 30c which is
free to move vertically, under the action of its own weight
and the tension of the fiber 4. In practice, the pulley 30c
99 is raised if there is an undesirable increase in the tension
of the fiber 4 and is lowered if there is an undesirable
decrease in the tension of the fiber 4, so as to keep the
said tension substantially constant. The pulley 30c may be
provided with a vertical position sensor (not shown) that is
99 designed to generate a signal indicating the vertical
position of the pulley 30c and therefore indicating the
tension of the fiber 4.

One or more pulleys 31 (or guiding members of other
types) are advantageously provided for guiding the fiber 4
99 from the tension-control device 30 to the winding device 9.

The winding device 9 comprises, in the illustrated
embodiment, a first, a second, a third and a fourth guiding
pulleys 36a, 36b, 36c, 36d, held by a support member 37, for
guiding the fiber 4 onto the reel 10. The winding device 9
99 further comprises a motorized device 33 for setting the reel
10 into rotation about its axis 34. The motorized device 33
may also be suitable for reciprocating the reel 10 along the
axis 34, so as to allow helix winding of the fiber 4 thereon

during drawing. Alternatively, the reel 10 may be axially fixed and the support member 37 (together with the pulleys 36a, 36b, 36c, 36d) may be mounted on a motorized slide (not shown in the drawing) designed to reciprocate along an axis
9 parallel to the reel axis 34.

A twist apparatus 40 is advantageously used for de-twisting the fiber, i.e. for removing an undesired elastic twist stored in the fiber 4 when spun. This undesired twist, which tends to generate circular birefringence in the fiber,
99 is produced during spinning of the fiber due to the presence of a fiber rotation constraint downstream the point of spinning.

The twist apparatus 40 may be used at the drawing stage, in particular to de-twist the fiber 4 during winding
99 thereof, or it may be used at a subsequent stage, for example during unwinding of the fiber 4 for re-spooling it on a bobbin suitable for shipment, as will be described in the following.

In practice, the twist apparatus 40 expressly applies
99 to the fiber a twist (which will be called "de-twist") in a direction opposite that of the undesired elastic twist resulting from spinning. In the following, with "direction opposite to the direction of spin", referred to the direction of the de-twist, it will be intended the direction
99 opposite to the direction of the twist resulting from spinning. The twist apparatus 40 may advantageously be integrated in the winding device 9 of the drawing tower 1. In particular, the support member 37 and the pulleys 36a, 36b, 36c, 36d may be part of the twist apparatus 40. With
99 reference to **Figure 9**, which illustrates one possible embodiment of the twist apparatus 40, the support member 37 is a rotating member having the shape of a two-prongs fork and comprising a hollow spindle 41 and a first and a second

arms 45, 46 extending from one end 41a of the hollow spindle 41. The spindle 41 is held coaxial to the axis 34 by a fixed frame 43 and is rotatably mounted thereon through bearings 44. The spindle 41 is driven by a DC motor (not shown in the drawing) through a belt transmission (also not shown in the drawing). In use, the spindle 41 is designed to be passed through by the fiber 4 along the axis 34.

The first and second arms 45, 46 are symmetrical to each other with respect to the axis 34 and have respective first portions 45a, 46a rigidly connected to the spindle 41 and extending away from the axis 34 opposite to each other, and respective second portions 45b, 46b parallel to the axis 34. The first portions 45a, 46a have a radial extension greater than the radius of the reel 10, and the second portions 45b, 46b have a length corresponding substantially to the length of the reel 10. The reel 10 is located between the second portions 45b, 46b of the arms 45, 46.

The first pulley 36a is positioned at the end of the spindle 41 facing the reel 10, and is designed to deviate the fiber 4 to the first arm 45. The second, third and fourth pulleys 36b, 36c, 36d are positioned along the second portion 45b of the first arm 45 and define a wavy path for the fiber 4 before it is fed to the reel 10. The function of the third pulley 36c (which is intermediate between the second pulley 36b and the fourth pulley 36d) is to avoid that the fiber 4 slips from pulleys 36b and 36d, and it might be dispensed for. The second arm 46 has only a balancing function and may carry three pulleys identical to pulleys 36b, 36c, 36d, to have the same distribution of weights as the first arm 45.

While the first, second and third pulleys 36a, 36b, 36c preferably have the respective axes parallel to each other and perpendicular to the axis 34, the fourth pulley 36d is

preferably tilted about an axis parallel to the axis 34, of such an angle that it lies on a plane that is tangent to the fiber bobbin when the reel 10 is half filled.

9 The twist apparatus 40 preferably comprises a fiber position sensor 48 (for example a device model Keyence FS-V11P FU-35FA) positioned between the fourth pulley 36d and the reel 10, to provide a control signal for the alternate axial motion of the reel 10 (Figure 9 shows, for example, two different positions of reel 10) or of the support member 37. In fact, as previously stated, a relative alternate motion shall be provided between the reel 10 and the support member 37 to allow helix winding of the fiber 4.

99 The drawing tower 1 may further comprise a control unit (not shown in the drawing), electrically connected to all the devices of the tower 1 to be controlled from the outside, and to all the sensors and the detectors present along the tower 1.

The drawing tower 1 operates as follows.

99 The supporting device 7 feeds the preform 3 to the furnace, where a lower portion thereof (the neckdown) is melted. The fiber 4 drawn from the neckdown is pulled down from the traction device 8 and wound onto the reel 10 by the winding device 9. Between the capstan 18 and the reel 10, the tension-control device 30 regulates the tension of the fiber 4.

99 As the fiber 4 is drawn, the sensors 13 and 14 monitor its tension and diameter. Such monitoring can be used to control the drawing process, for example by acting on the traction speed. When exiting the furnace 6, the fiber 4 is cooled by the cooling device 12 and it is coated with two protective layers by the coating devices 15, 16.

The coated fiber 4 is then subjected to a unidirectional and substantially constant spin by the

spinning device 20. This is obtained by setting into rotation the rotating member 23 about the axis 2 at a constant speed. Each turn of the rotating member corresponds to one turn of the fiber 4 about its axis.

9 The spin rate is selected in such a way that the effects of the imperfections and irregularities of the fiber 4 are rendered substantially uniform in a length of the fiber 4 equal to at least the shortest typical beat length L_B . As a result, when signals are transmitted into the 99 fiber, there is an exchange of power between the fundamental propagation modes and, therefore, a reduction of the PMD. Thus, it is possible to significantly reduce the negative effects caused by the asymmetric stress conditions and by the imperfections of shape intrinsically present in the 99 fiber 4.

The Applicant has observed that the higher the spin rate, the better the performances of the fiber in terms of PMD. However, the higher the spin rate, the higher the elastic twist to be removed. The Applicant has verified that 99 a spin rate between 1 and 8 turns/m allows reducing the PMD at acceptable values and at the same time introduces an amount of elastic twist that can be efficiently removed by the technique here described.

When spun, the fiber 4 transmits a corresponding torque 99 upstream and downstream. Upstream, the torque is transmitted to the preform neckdown, where the plastic deformation of the melted glass "absorbs" the torque and "transforms" it into an intrinsic orientation of the birefringence axes of the fiber 4. This intrinsic torsion is frozen into the fiber 99 4 as the fiber cools. Downstream, in the absence of any countermeasure, the torque would be transmitted as far as the reel 10, where the fiber 4, once wound, would keep a residual elastic twist. This elastic twist would introduce,

if not controlled, an undesired circular birefringence in the fiber 4.

In order to control the residual twist in the wound fiber 4, the fiber 4 is de-twisted by the twist apparatus 40. In practice, the rotating support member 37 is made to rotate about the axis 34, in a sense opposite to the spinning sense (more precisely, as previously stated, in a sense opposite to that of the elastic twist generated by spinning). Each turn of the support member 37 about the axis 34 corresponds to one turn of the fiber 4 about its axis. The torque transmitted along the fiber 4 downstream the spinning device 20 is then at least reduced by the twist apparatus 40 before the fiber is wound onto the reel 10.

In detail, the fiber 4, after passing through the spindle 41, is deviated by the first pulley 36a towards the first arm 45, is herein conveyed along the second portion 45b with the required tension by the second and third pulleys 36b, 36c, and is finally fed to the reel 10 by the fourth pulley 36d, in a direction substantially perpendicular to the axis 34. While being rotated about the axis 34, the reel 10 is also reciprocated along the axis 34, so as to allow an helical winding of the fiber 4.

The signal of the sensor 48 is used to control the speed of the alternate motion of the reel 10, so that the fiber 4 is always made to pass in a predetermined position of the sensor 48.

The Applicant has found that the PMD of the fiber 4 can be reduced to a minimum by imparting to the fiber, after it has been spun, a twist that not only removes the elastic twist generated by the spinning action, but also introduces a positive residual twist, i.e. a twist in the opposite sense. The Applicant has verified that a positive residual twist between 0 and 1.5 turns/m, preferably between 0.3 and

1 turns/m, allows reducing the PMD of spun fibers in a wide range of spin rates, at least up to 8 turns/m.

As previously stated, fiber de-twisting may be performed, instead of during the drawing process, at a stage subsequent to drawing, and may be associated with the operation of unwinding of the fiber 4 from reel 10. For example, de-twisting may be performed during re-spooling of the fiber 4 onto a shipping spool to be shipped to a customer or during screening operations. Screening is a test operation, performed on an optical fiber to check the strength thereof, which comprises applying a predetermined longitudinal tension to the fiber 4 while it runs in a predetermined path, usually defined by pulleys.

As shown in **Figure 10**, the twist apparatus 40 may for example be used with the fiber 4 moving in the opposite direction, so as to perform fiber de-twisting while the fiber 4 is unwound. In particular, **Figure 10** illustrates a re-spooling assembly 70 comprising an unwinding device 9' for unwinding the fiber 4 from the reel 10 and a further winding device 71, including guiding pulleys 73, for re-winding the fiber 4 onto a different reel 74. The unwinding device 9' substantially corresponds to winding device 9, but operates in the opposite direction, to unwind the fiber 4. In this case, the twist apparatus 40 is integrated in the unwinding device 9' for de-twisting the fiber 4 as it is unwound from the reel 10. The re-spooling assembly 70 may also comprise a screening device 72, for example of the type described in US 5,076,104.

Figure 11 shows a different embodiment of the twist apparatus, indicated with reference numeral 50. The twist apparatus 50 comprises a fixed frame 51 supporting the reel 10 along the axis 34, and a rotating member 52 for twisting the fiber 4 as it is wound onto the reel 10 or unwound

therefrom.

The rotating member 52 comprises a first and a second spindles 53, 54, supported by the frame 51 coaxially to the axis 34, and a flexible arch member 55 connecting the two
9 spindles 53, 54 over the reel 10, for the passage of the fiber 4.

The fixed frame 51 comprises two external support members 56, 57 and two internal support members 58, 59 substantially aligned to each other along the axis 34. The
99 external support members 56, 57 are cylindrical and the member 57 has an internal passage for the fiber 4, along the axis 34. The reel 10 is positioned between the internal support members 58, 59 and it is supported thereby. The reel 10 is connected to a motor (not shown in the drawing)
99 through a belt transmission 60.

The spindles 53, 54 are opposite to each other with respect to the reel 10 and are connected to a same motor (different from that of the reel 10 and not shown in the drawing) through respective belt transmissions 62 (only one
99 of which is illustrated), so that they can be rotated at a same speed. Each of the spindles 53, 54 is positioned between a corresponding external support member 56, 57 and a corresponding internal support member 58, 59. The first spindle 53 carries internally a pulley 67 tangent to the
99 axis 34 that allows the passage of the fiber 4 between the arch member 55 and a further pulley 69 tangent to the axis 34 carried by the internal support member 58. The second spindle 54 carries internally a further pulley 68 tangent to the axis 34 allowing the passage of the fiber 4 between the
99 external support member 57 and the arch member 55. One or more further pulleys are provided for guiding the fiber to or from the reel 10.

The flexible arch member 55 is preferably made of

carbonium and forms a bridge over the reel 10 for the passage of the fiber 4 between the spindles 53, 54. The arch member 55 may be provided with equidistant guiding U-bolts 61, preferably made of ceramic and suitable to guide the fiber 4 along the arch member 55. Alternatively, the arch member 55 may be provided with a guiding tube (not shown in the drawing), which offers the advantage of an easier set-up before the process start, allowing blowing of the fiber 4 from one end to the other of the arch member 55.

99 The apparatus 50 is herein below described when operating for winding the fiber onto the reel 10. Similarly to the apparatus 40, the apparatus 50 may operate in the opposite direction to unwind the fiber 4 from the reel 10, for example in the re-spooling assembly 70 of Figure 10.

99 The fiber 4 is received through the member 57 and a first portion of the second spindle 54, where it is deviated by the pulley 68 to the arch member 55; the fiber 4 then runs over the entire arch member 55 and enters the first spindle 53, where it is further deviated by the pulley 67 towards the internal support member 58 along the axis 34; then, the fiber is further deviated by the pulley 69 and it is finally fed to the reel 10.

) The amount of twist to be applied to the optical fiber 4 for obtaining the desired amount of residual twist may be determined according to the following technique. In a first step, a test fiber section only subjected to spin is drawn. This test fiber section can be obtained, for example, by operating the drawing tower 1 of Figure 7 with the twist apparatus 40 off (i.e. with the rotating member 37 in a staying condition) for a predetermined time. Then, the residual twist accumulated in the test fiber section wound on the reel 10 is measured in the following way.

The reel 10 is hanged on a support located at a

predetermined height, for example at 2 m above ground. A corresponding length of fiber is unwound from the reel 10, keeping it under a moderate tension. The upper end of the unwound fiber section is secured to the reel surface, while
7 the free end is marked, for example with a small piece of tape (having a negligible weight) and it is left free to rotate. The measurement resolution depends on the length of the unwound fiber section. For a fiber length of 2 m, the number of turns can be measured with a resolution of about $\frac{1}{4}$
99 turns over 2 m, so that a resolution of about 0.125 turns/m can be obtained. If a higher resolution is required, a longer fiber can be used.

The Applicant has observed that the presence of the fiber coating shall be taken into consideration for an
99 accurate measurement of the residual twist due to spinning, since a residual twist is also accumulated in the fiber under the coating. Accordingly, after the residual twist of the coated fiber has been measured in the way previously described, the free end of the coated fiber is blocked and
99 the coating is completely removed (using a conventional Miller stripper). The fiber is then left again free to rotate, and the additional rotation of the fiber is measured with the same resolution as above.

The operation is repeated over consecutive fiber
99 sections of predetermined length, for example every 2 m, to reach a predetermined total measured length, for example between 20 and 60 m. The mean value is used to label the torsion value of the fiber.

After the residual twist due to spinning has been
99 measured, the fiber drawing may be continued with the twist apparatus 40 turned on, suitably set to obtain the desired residual twist.

It is thus possible to obtain an optical fiber having a

unidirectional intrinsic spin and an elastic twist equal to zero in module, or opposite to said spin and greater than zero in module.

9 The unidirectional intrinsic spin may be substantially constant or variable. In this second case, the spin function is preferably obtained by superposing a substantially constant function and a periodic function, and the twist is applied so as to vary the average value of the residual twist to the desired value. The elastic twist applied to the 99 fiber is preferably comprised in module between 0 and about 1.5 turns/m, more preferably between about 0.3 and 1 turns/m.

Fibers with both helicities, clockwise and counter clockwise, are produced by the process previously described 99 by changing the rotation direction of the spinning device and of the twisting device. Once two sets of fibers (σ_+ and σ_-) with opposite helicity have been produced, spans of predetermined length of these fibers are used in a cabling process of a known type to produce an optical cable as 99 previously described.

Although the present invention has been disclosed and described by way of some embodiments, it is apparent to those skilled in the art that several modifications to the described embodiments, as well as other embodiments of the 99 present invention are possible without departing from the scope thereof as defined in the appended claims.

For example, although in the invention embodiment shown in **Figure 2** a strict alternation of unidirectionally spun fiber spans having mutually opposite spinning helicity is 99 provided for, this is not to be construed as a limitation of the present invention, because an optical fiber link might also be produced by splicing unidirectionally spun optical fiber spans of opposite spinning helicity without

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necessarily respecting such a strict alternation.

Moreover, the optical fiber link may comprise one or more spans of unspun optical fibers or of alternately spun optical fibers, spliced to the unidirectionally spun fibers
9 or arranged between two spans of unidirectionally spun fiber.

CLAIMS

1. An optical fiber link (300) comprising a plurality of optical fiber spans (305_(k-1), 305_k, 305_(k+1), 305_(k+2), 9 305_(k+3), 305_(k+4), 305_(k+5), 305_(k+6)) joined one to the other, characterized in that

said plurality of optical fiber spans includes at least one first unidirectionally-spun optical fiber span (305_(k-1), 305_(k+1), 305_(k+3), 305_(k+5)) and at least one second 99 unidirectionally-spun optical fiber span (305_k, 305_(k+2), 305_(k+4), 305_(k+6)) having mutually opposite spinning directions.

2. The optical fiber link according to claim 1, in 99 which the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span are joined to each other.

3. The optical fiber link according to claim 1, in 99 which said plurality of optical fiber spans includes a plurality of first optical fiber spans, and a plurality of second optical fiber spans, the first optical fiber spans and the second optical fiber spans being spans of unidirectionally spun optical fibers having mutually 99 opposite spinning directions, and wherein the first optical fiber spans and the second optical fiber spans are alternated to each other in the optical fiber link.

4. The optical fiber link according to claim 1, in 99 which the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span have substantially a same length.

5. The optical fiber link according to claim 1, in which the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span have substantially a same spin rate.

¶

6. The optical fiber link according to claim 3, in which the number of first optical fiber spans and second optical fiber spans is odd.

¶¶ 7. An optical cable line (80) including a plurality of optical cable trunks ($805_{(k-1)}$, 805_k , $805_{(k+1)}$, $805_{(k+2)}$, $805_{(k+3)}$, $805_{(k+4)}$) joined to each other, characterized in that said plurality of optical cable trunks comprises at least a first optical cable trunk and a second optical cable trunk, ¶¶ the first optical cable trunk including a first optical fiber span ($305_{(k-1)}$, $305_{(k+1)}$, $305_{(k+3)}$, $305_{(k+5)}$) unidirectionally-spun in a first direction, and the second optical cable trunk including a second optical fiber span (305_k , $305_{(k+2)}$, $305_{(k+4)}$, $305_{(k+6)}$) unidirectionally-spun in a ¶¶ second direction opposite to the first direction, the first and the second optical fiber spans being optically linked to each other.

¶¶ 8. The optical cable line according to claim 7, in which the first and the second optical fiber spans are joined to each other.

¶¶ 9. The optical cable line according to claim 7, in which the first and the second optical fiber spans have substantially a same length.

10. The optical cable line according to claim 7, in which the first and the second optical fiber spans have

substantially a same spin rate.

11. The optical cable line according to claim 7, in which the plurality of optical cable trunks include a plurality of first optical fiber spans ($305_{(k-1)}$, $305_{(k+1)}$, $305_{(k+3)}$, $305_{(k+5)}$), and a plurality of second optical fiber spans (305_k , $305_{(k+2)}$, $305_{(k+4)}$, $305_{(k+6)}$) joined to each other to form an optical fiber link (800), the first optical fiber spans and the second optical fiber spans being unidirectionally-spun optical fibers having mutually opposite spin directions, and wherein the first optical fiber spans and the second optical fiber spans are alternated to each other in the optical fiber link.

12. The optical cable line according to claim 7, in which at least one optical cable trunk of said plurality of optical cable trunks has an optical core including a plurality of unidirectionally-spun optical fiber spans having a same spin direction.

13. The optical cable line according to claim 7, in which at least one optical cable trunk of said plurality of optical cable trunks has an optical core including at least two unidirectionally-spun optical fiber spans having opposite spin directions.

14. The optical cable line according to claim 7, in which the total number of optical cable trunks is odd.

15. A method of realizing an optical fiber link (300), comprising:

providing at least a first span of optical fiber ($305_{(k-1)}$, $305_{(k+1)}$, $305_{(k+3)}$, $305_{(k+5)}$), unidirectionally-spun in a first direction;

providing at least a second span of optical fiber
(305_k , $305_{(k+2)}$, $305_{(k+4)}$, $305_{(k+6)}$), unidirectionally-spun in a
second direction opposite to the first direction; and

joining the first span and the second span together at
9 a respective end thereof.

16. A method of producing an optical cable, comprising
providing a plurality of optical fibers to a cable
manufacturing line, wherein said plurality of optical fibers
99 comprises at least a first optical fiber ($305_{(k-1)}$, $305_{(k+1)}$, $305_{(k+3)}$, $305_{(k+5)}$) being unidirectionally-spun in a
first direction, and at least a second optical fiber
(305_k , $305_{(k+2)}$, $305_{(k+4)}$, $305_{(k+6)}$) being unidirectionally-spun in
a second direction opposite to the first direction.

99

17. A method of realizing an optical cable line,
comprising:

forming a plurality of optical cable trunks
(805_k , ..., $805_{(k+4)}$), each one including at least one optical
99 fiber span ($305_{(k-1)}$, ..., $305_{(k+6)}$); and

joining the optical cable trunks one to another;
characterized in that

the step of forming a plurality of optical cable trunks
comprises forming at least one first trunk including a first
99 optical fiber span ($305_{(k-1)}$, $305_{(k+1)}$, $305_{(k+3)}$, $305_{(k+5)}$)
unidirectionally-spun in a first direction, and forming at
least one second trunk including a second optical fiber span
(305_k , $305_{(k+2)}$, $305_{(k+4)}$, $305_{(k+6)}$) unidirectionally-spun in a
second direction opposite to the first direction, and in
99 that said joining the optical cable trunks one to another
includes optically linking the first optical fiber span to
said second optical fiber span.

LOW PMD OPTICAL FIBER LINK, AND METHOD OF MAKING THE SAME

* * * * *

ABSTRACT

An optical fiber link (300) comprises a plurality of
9 optical fiber spans ($305_{(k-1)}, \dots, 305_{(k+6)}$) joined one to the
other, the plurality of optical fiber spans including at
least one first unidirectionally-spun optical fiber span
($305_{(k-1)}, 305_{(k+1)}, 305_{(k+3)}, 305_{(k+5)}$) and at least one second
unidirectionally-spun optical fiber span
99 ($305_k, 305_{(k+2)}, 305_{(k+4)}, 305_{(k+6)}$) having mutually opposite
spinning directions.

(Figure 2)

99

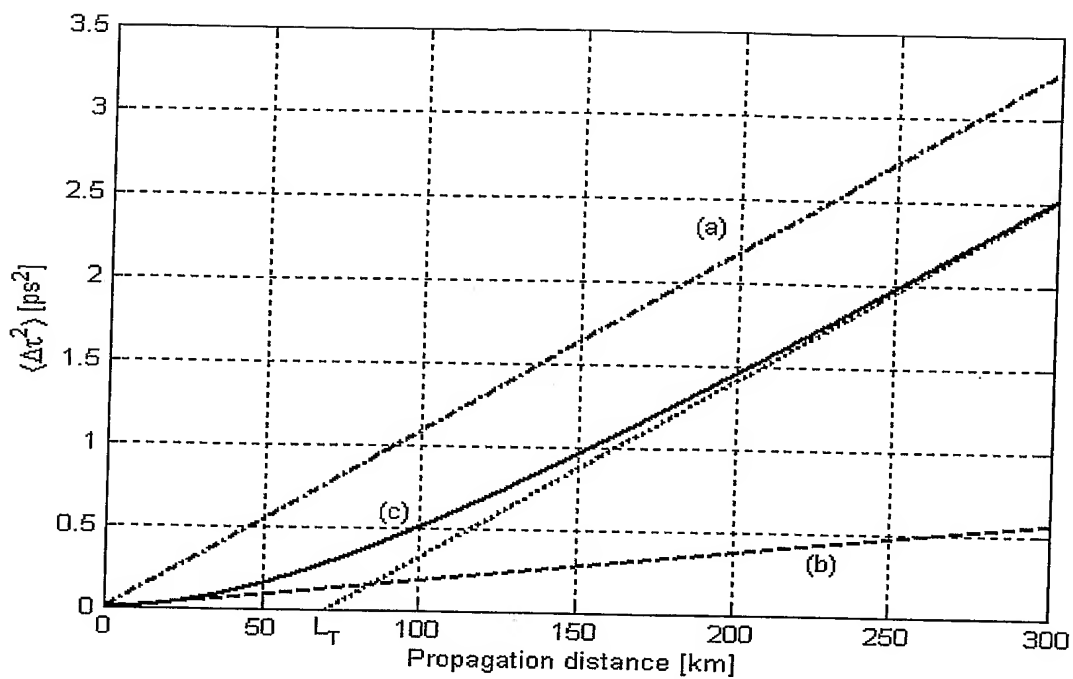


FIG. 1

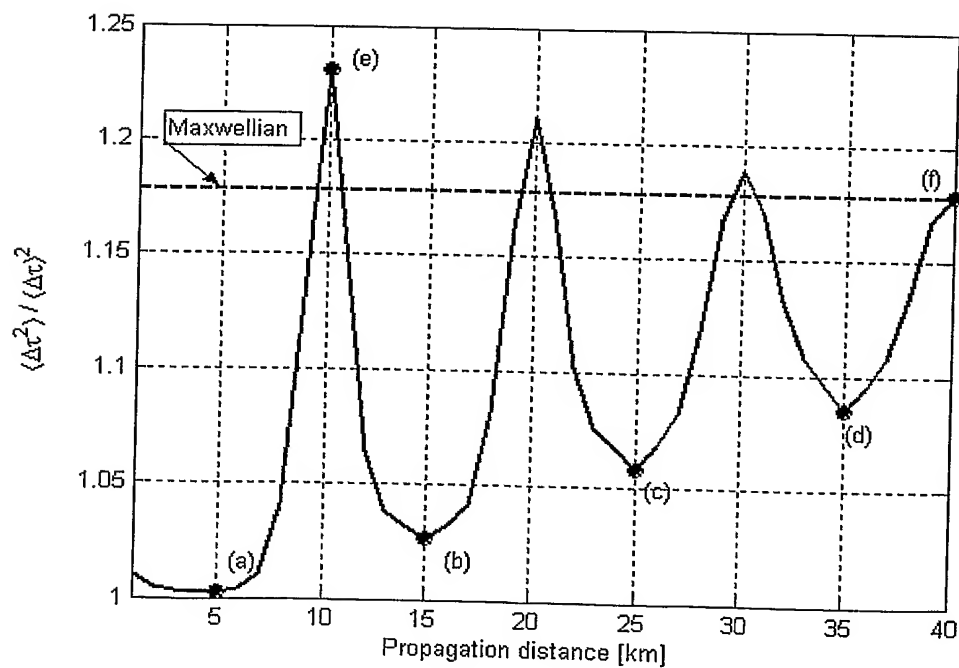


FIG. 5

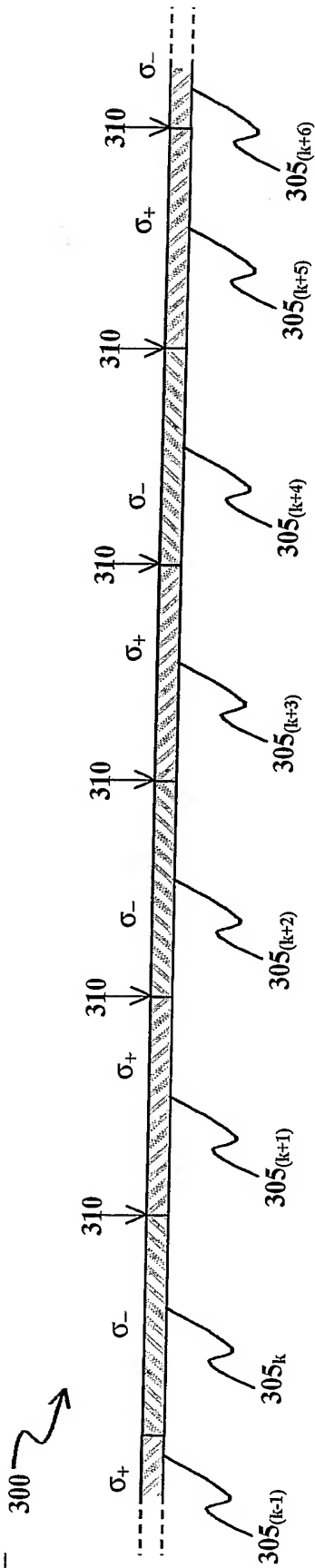


FIG. 2

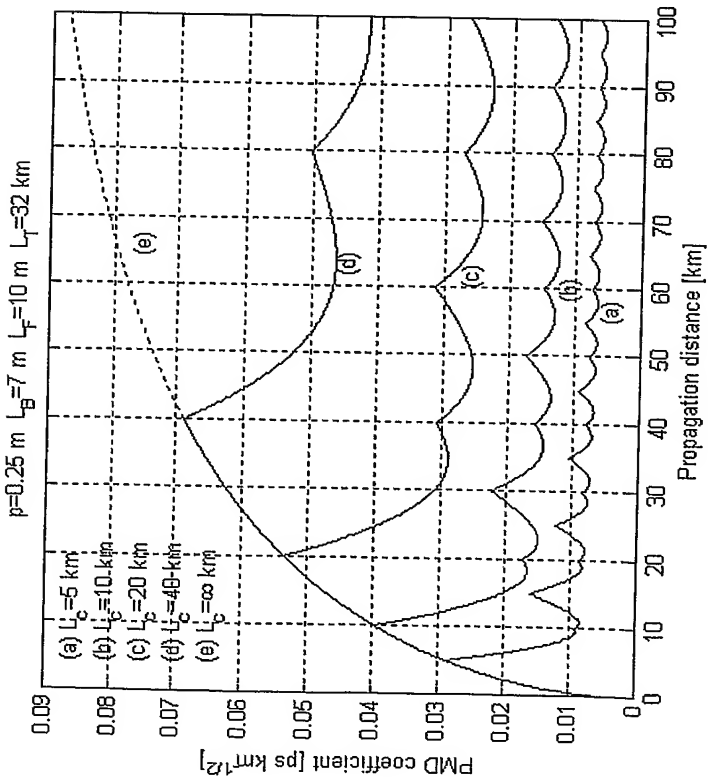


FIG. 3A

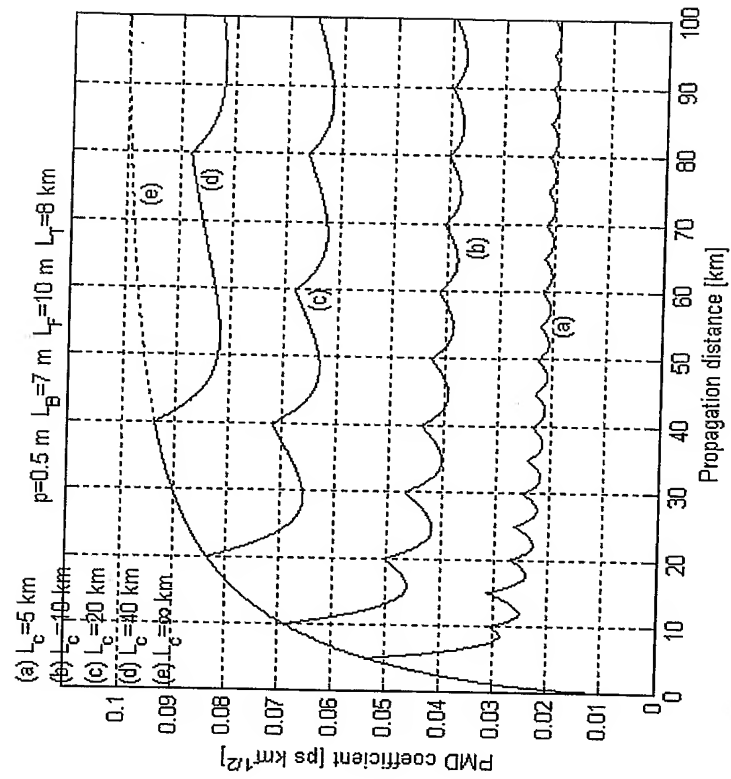


FIG. 3B

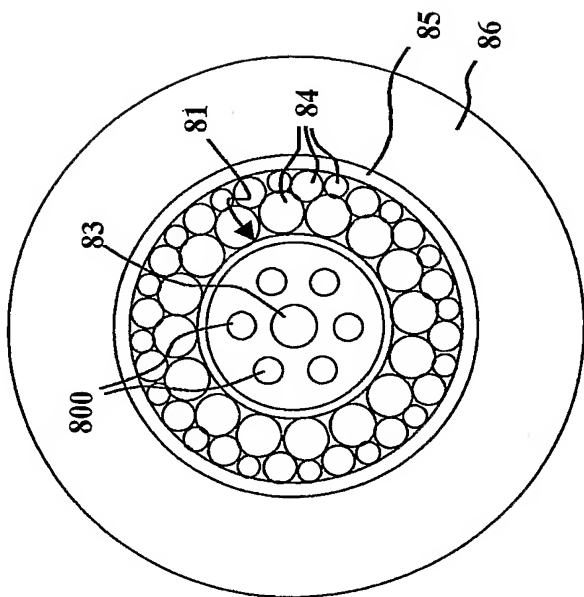


FIG. 4A

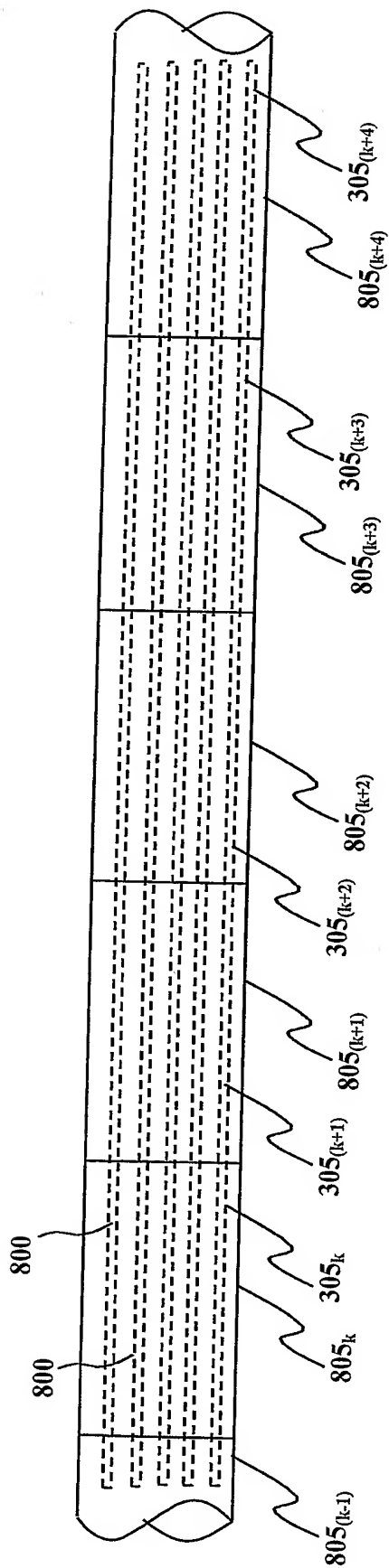


FIG. 4B

FIG. 6A

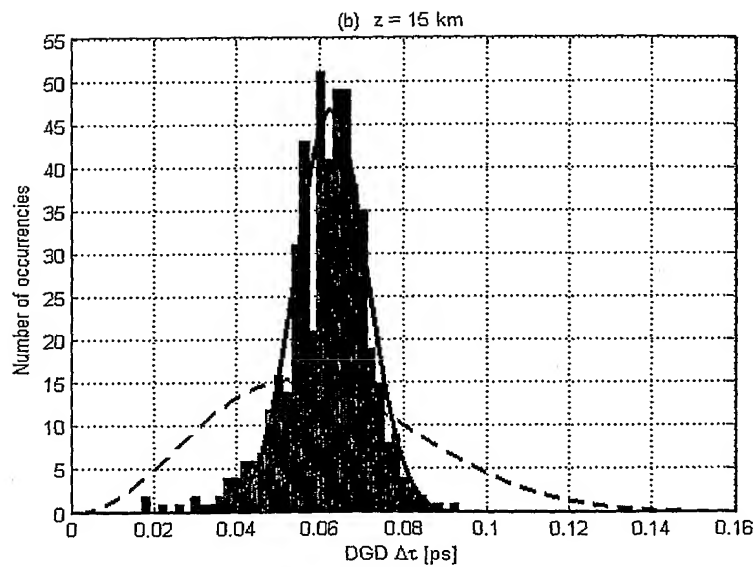
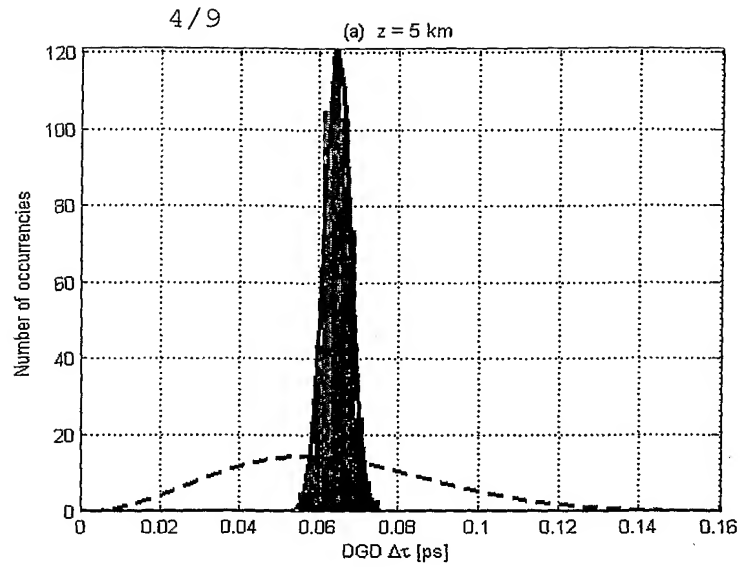


FIG. 6B

FIG. 6C

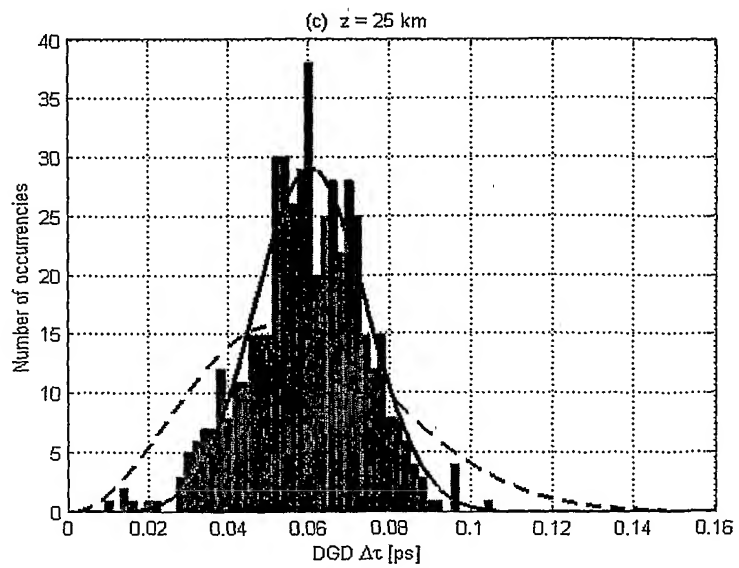


FIG. 6D

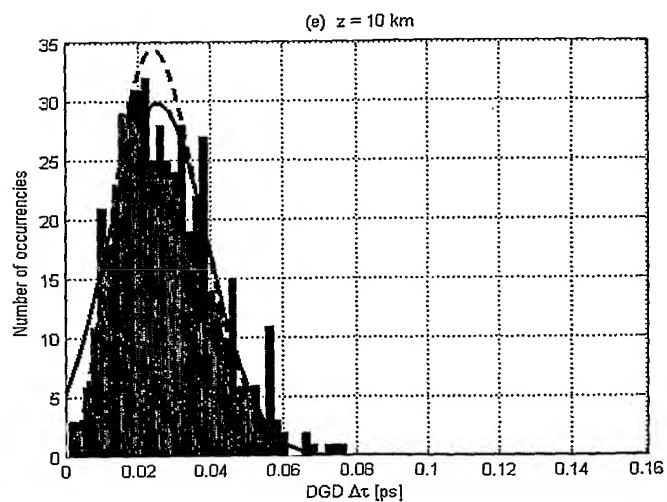
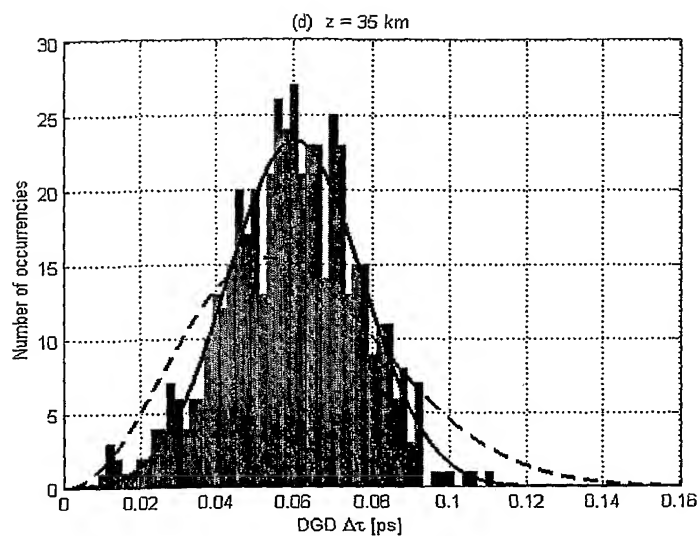
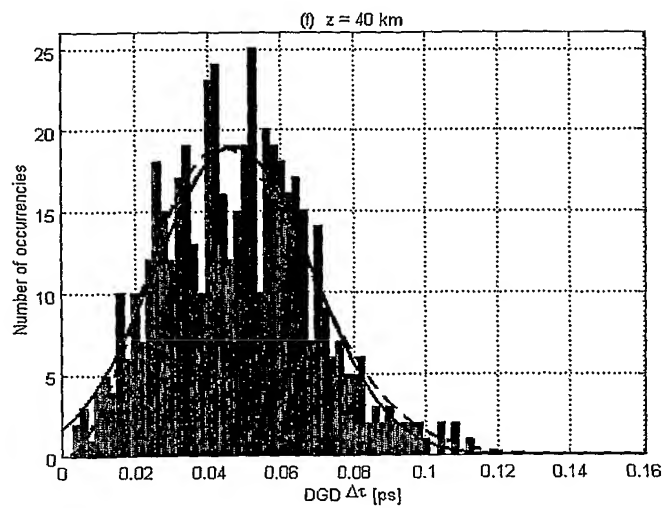


FIG. 6E

FIG. 6F



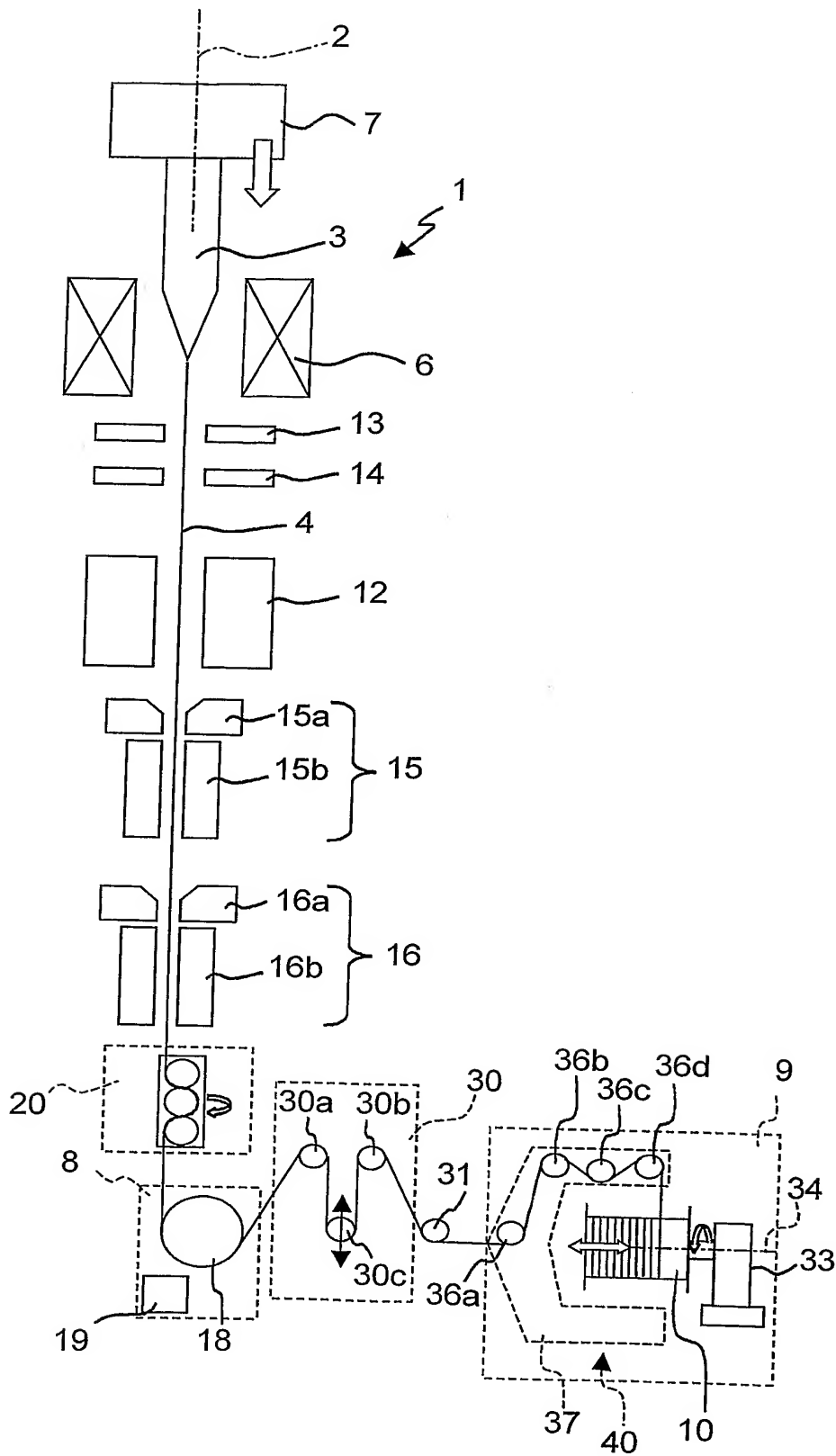
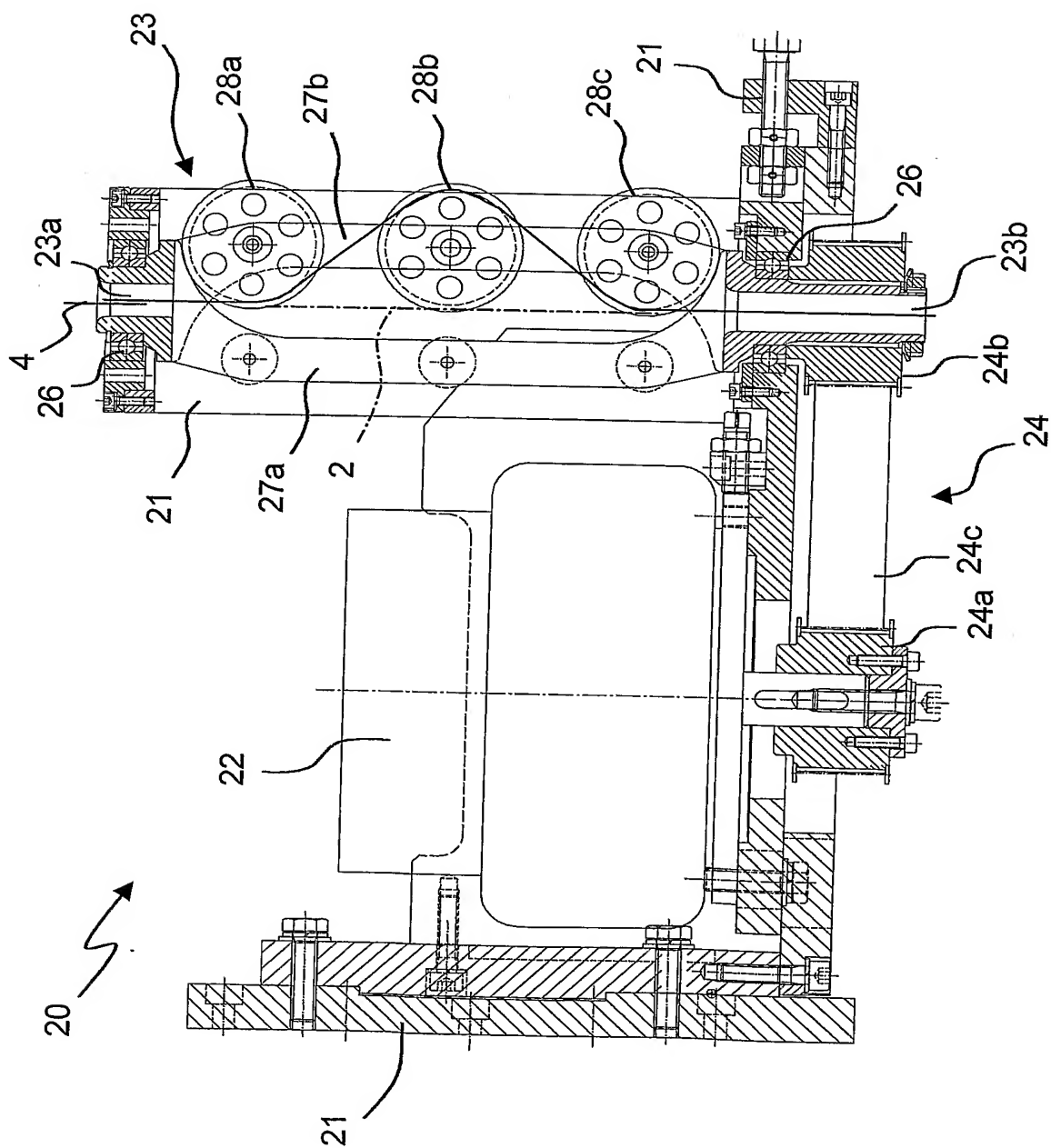


FIG. 7

FIG. 8



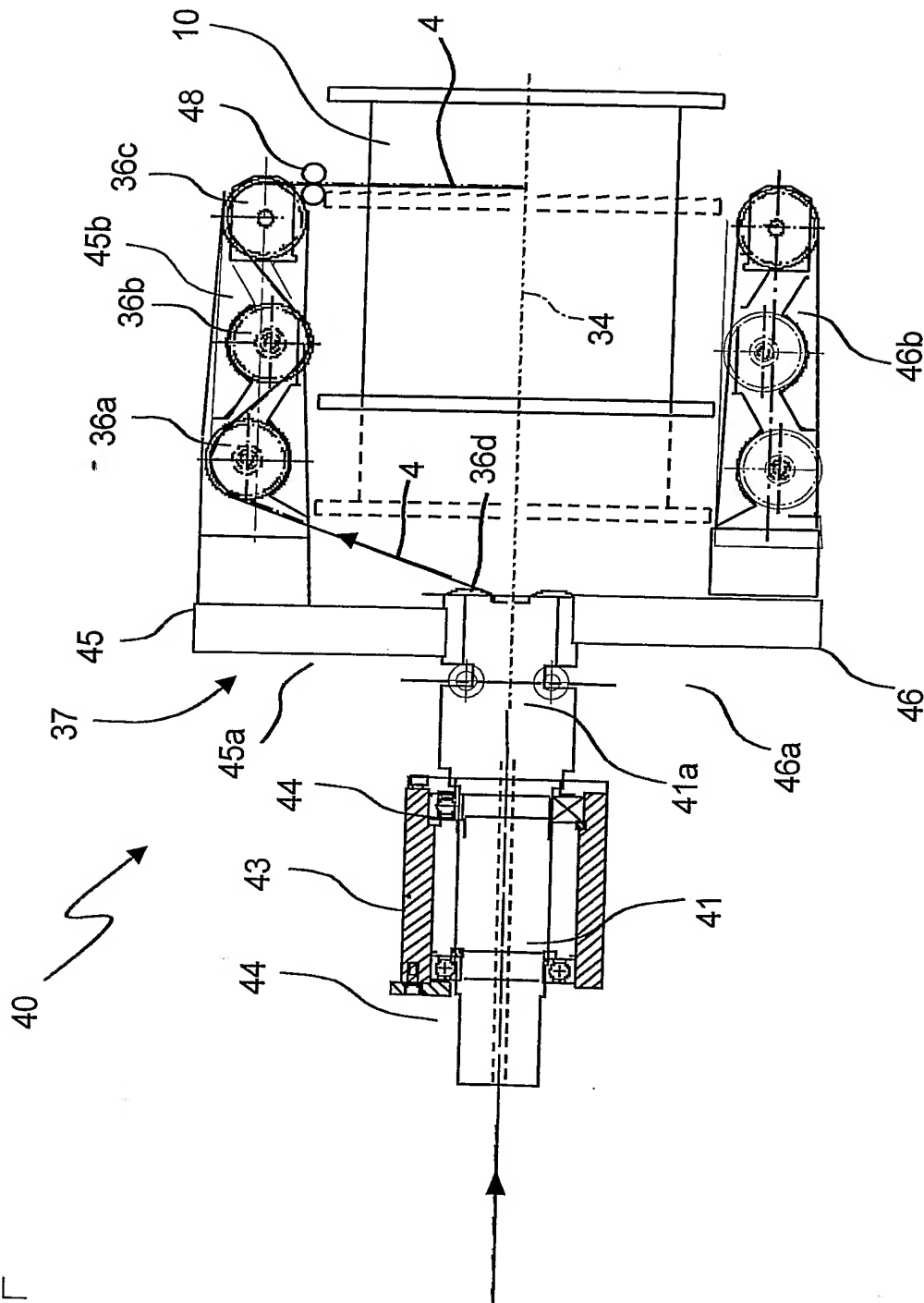


FIG. 9

